precise and practical one for a calculation of the band or of a perturbation thereon. But a numerical estimate of the errors cannot precede a better experimental knowledge of the material.

There is something disturbing about Table XVIII. The values for the uniaxial strain potentials are in bad disagreement. In our opinion, the results from the mobility measurements only prove that the intravalley acoustical scattering is an improper model for PbTe: another kind of scattering must be thought of. The results from the piezoresistance experiment are not too reliable; at least, let us not rely on them more than Ilisavskiĭ does.[20] It is not that Ilisavskiĭ's measurements are doubtful, but that the model he assumed to derive the numbers for the deformation potentials is too simple for the complex situation in PbTe. In particular, Ilisavskiĭ was not able, for lack of data, to compensate the degeneracy of the electronic gas. Depending on the degree of degeneracy, his model can underestimate D_u by a factor of 2, 3, or more, which would bring his numbers much closer to ours. So, it is very possible that our numbers are very near the truth.

Finally, a word about previous works. Kleinman and Goroff have calculated the deformation potentials for silicon.[24] Their work differs from the present one in that:

(1) In the case of silicon, a uniaxial strain can remove the inversion center; and there is no such complication in PbTe.

(2) Their method was based on the orthogonalized-plane-wave method, and ours is based on the APW.

(3) There is the all-important problem of definition of the crystal potential. As long as the potential is not self-consistent, it is difficult to know, *a priori*, how good it is. The only possible basis to judge a potential lies in the quality of the results. It is the author's opinion that a good potential should consistently give good results, in terms of the order of levels, $\mathbf{k}\cdot\mathbf{p}$ perturbation, strain deformation or any other perturbation. And we are pleased with the results obtained so far.

ACKNOWLEDGMENT

The writer is specially indebted to Professor George W. Pratt, Jr. for suggesting this work and for his continued interest and support.

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Magnetoresistance of Iron Whiskers*

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Transverse magnetoresistance measurements on iron whiskers with axes along ⟨100⟩, ⟨110⟩, and ⟨111⟩ have been made in fields up to 50 kOe. Measurements have been made on whiskers with diameters ranging from 40 to 400 μ. Sharp minima observed in the rotation diagrams measured at 50 kOe for all three orientations are consistent with the existence of open orbits along ⟨100⟩ and ⟨110⟩ directions. The field dependence curves show a region of negative magnetoresistance at low fields and at high fields the resistance varies as B^m, where $1<m<2$. The extent of the negative magnetoresistance region depends both on the field orientation and the diameter of the whisker and appears to be correlated with the domain structure. A size effect has also been observed on the field dependence of resistance at high fields and on the residual resistance ratio $\rho_{RT}/\rho_{4.2}$°. Values of $\rho_{RT}/\rho_{4.2}$° range from 200 to 2000 for the whiskers which have been measured.

INTRODUCTION

MAGNETORESISTANCE measurements on single crystals of ferromagnetic metals have recently been used to obtain preliminary information on the nature of the Fermi surface in these metals.[1,2] In the case of iron, whiskers offer one of the best possibilities of obtaining well-oriented high-purity crystals for such studies. De Haas–van Alphen studies on iron whiskers by Gold[3] have already been very successful, and preliminary data on Hall effect and magnetoresistance have been reported by Dheer.[4] Reed and Fawcett[5] have also reported initial results on the magnetoresistance in iron whiskers along with data on strain annealed crystals.

In this paper we report on the results of transverse magnetoresistance measurements on iron whiskers grown by the hydrogen reduction of ferrous chloride.

* Research supported by the U. S. Atomic Energy Commission and the U. S. Office of Naval Research.

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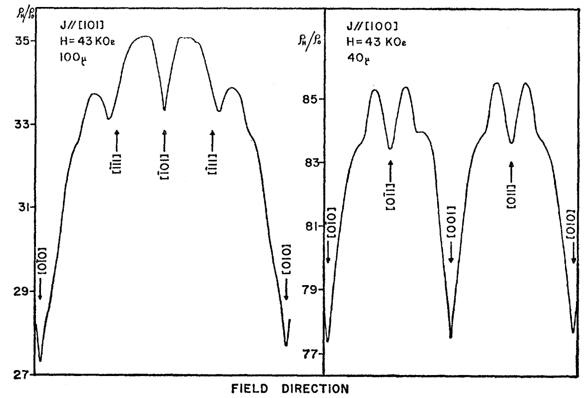

FIG. 1. Transverse magnetoresistance rotation diagrams recorded for ⟨100⟩ and ⟨110⟩ axial whiskers at 43 kOe.

The measurements have been made at 4.2°K in a superconducting solenoid which produces fields up to 50 kOe. The whiskers were mounted in a sample holder with the whisker axis transverse to the solenoid axis. The whisker could then be rotated about its own axis through an angle of 220°. Both the transverse rotation diagrams and the field dependence curves have been measured for a number of orientations and diameters. The effects of domain structure on the low field magnetoresistance have also been studied in some detail.

TRANSVERSE ROTATION

Rotation curves of the transverse magnetoresistance have been recorded at fields up to 50 kOe for whiskers ranging in diameter from 40 to 400 μ and with axes oriented along ⟨111⟩, ⟨100⟩, and ⟨110⟩. At 50 kOe the rotation curve obtained for the ⟨111⟩ axial whiskers shows the expected sixfold symmetry with minima occurring for field directions along ⟨112⟩ and ⟨110⟩. Maxima are located symmetrically on either side of the minima. For the ⟨100⟩ axial whiskers the transverse rotation curve shows fourfold symmetry with minima for field along ⟨100⟩ directions and very shallow minima for field along ⟨110⟩ directions. Maxima are again located symmetrically on either side of the minima. The ⟨110⟩ axial whiskers show sharp minima for field directions along the low index directions ⟨100⟩ and ⟨110⟩, while rather shallow minima occur for field directions near ⟨111⟩. These minima are not however exactly coincident with ⟨111⟩. Figure 1 shows typical rotation diagrams obtained for the ⟨100⟩ and ⟨110⟩ axial whiskers in fields near 50 kOe while Fig. 2(a) shows the curve for a ⟨111⟩ axial whisker. The major features shown in these curves are typical of the high field curves obtained for all diameters of whisker in the 40–400 μ range.

Figure 3 shows a stereographic plot of the minima observed for the various current axes which have been measured. These minima occur for directions of H which lie in the $\{100\}$ and $\{110\}$ planes. In the case of the low index current axes measured in the transverse orientation ($\mathbf{H}\perp\mathbf{J}$), minima occur for every $\{110\}$ and $\{100\}$ plane which the field crosses.

This anisotropy observed in the high-field rotation curves appears to be definitely related to the topology of the Fermi surface and can be explained by the presence of open orbits on the Fermi surface. Reed and Fawcett[5] have observed similar minima in strain annealed samples and in iron whiskers with their axes lying in the $\{100\}$ plane. They have concluded from their data that the minima are due to sets of periodic open orbits with net directions along ⟨001⟩ and ⟨110⟩. The functional dependence of the resistance due to open orbits is described in the high-field region by

$$\rho(\alpha)=A\mathbf{B}^2\cos^2\alpha+C\,,$$

where A and C are constants and α is the angle between the current axis and the open orbit direction. The minima due to open orbits will therefore correspond to angles α in the neighborhood of $\pi/2$ and will not be present when α is near zero. If one assumes open orbits along ⟨100⟩ and ⟨110⟩, then the condition $\alpha=0$ will be satisfied when $\mathbf{H}$ lies in a $\{110\}$ or $\{100\}$ plane whose perpendicular is parallel to the current direction. In the case of a low index current axes in the transverse

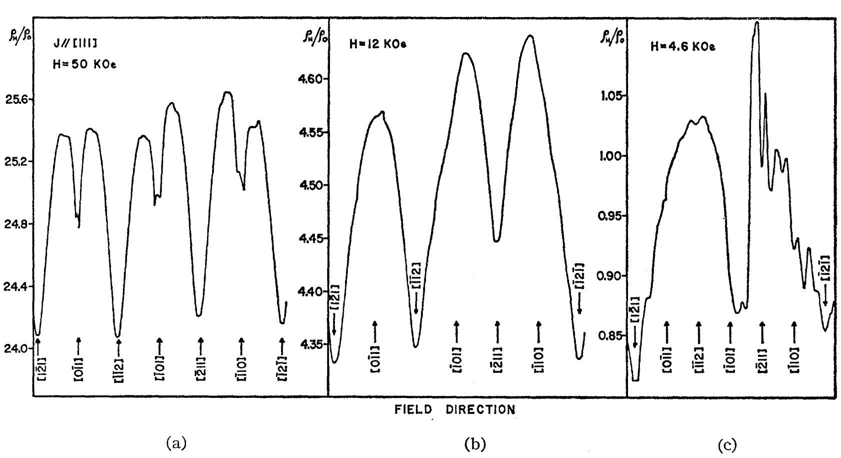

FIG. 2. Transverse rotation diagrams measured for a ⟨111⟩ axial whisker 440 μ in diameter. (a) $H=50$ kOe, (b) $H=12$ kOe, (c) $H=4.6$ kOe.

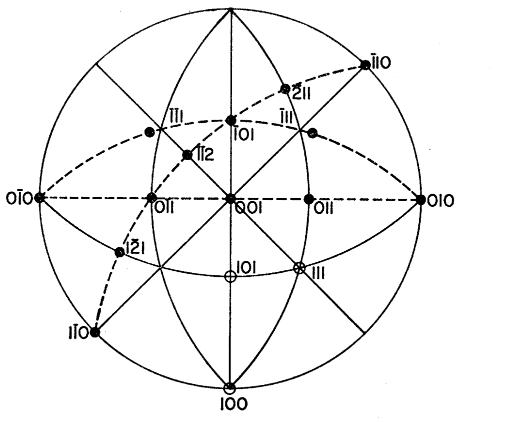

FIG. 3. Stereogram indicating the directions of **H** for which minima were observed. ● indicates position of minimum. Dashed lines indicate field sweep corresponding to current axes indicated by ○. Solid lines indicate {100} and {110} planes. Field directions lying in these planes will be perpendicular to open orbit directions.

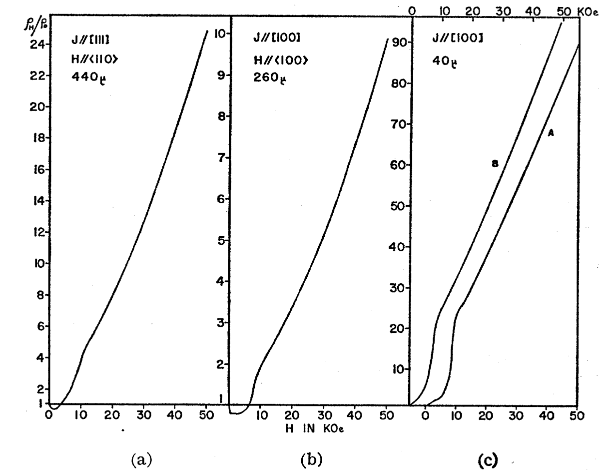

FIG. 4. Field dependence curves measured for various diameters and orientations of iron whisker. (a) ⟨111⟩ whisker, 440-μ diameter; (b) ⟨100⟩ whisker, 260-μ diameter; (c) ⟨100⟩ whisker, 40-μ diameter. **H**∥⟨100⟩ for curve A. **H** 20° from ⟨100⟩ for curve B.

orientation, the application of this criterion may be complicated by special cases corresponding to the intersection of two {110} or {100} planes as pointed out by Reed and Fawcett[5] for the ⟨100⟩ current axis. We have tipped our crystals away from the transverse orientation along arbitrary high index planes and find that for α near zero the minima are not observed in agreement with the observations of Reed and Fawcett.[5]

For a compensated metal like iron the field dependence of resistance in high fields is in general described by $\rho(\mathbf{B})/\rho(0)=CB^m$ where $1<m<2$. However, in the special case of open orbits making an angle near 90° to the current axis, the resistance would be expected to saturate in high enough fields. Reed and Fawcett[5] have observed a trend toward saturation at the minima observed in iron whiskers in fields up to 100 kOe. We have made field dependence measurements up to 50 kOe, but have not detected a clear trend toward saturation at the minima. The value of m at the minima is found to be consistently lower than for other orientations of field, but is still greater than 1. This is probably due to the fact that the field is not high enough to clearly show the saturation for whiskers of the present purity. We have also found that the value of m for a given orientation changes substantially as a function of the diameter of the whisker. Field dependence curves are shown in Figs. 4 and 7 and will be discussed in more detail in the next section.

We have also studied the rotation diagrams as a function of magnetic field. Major changes are observed at lower fields where contributions of domain boundaries and magnetization switching begin to dominate over the regular electronic magnetoresistance observed at high fields. These changes in the rotation curves begin to appear at fields around 12 kOe where a sharp break is observed in the field dependence curve. The series of curves in Fig. 2 demonstrate the effect observed in a 440-μ ⟨111⟩ axial whisker. As the field is lowered to 12 kOe, the minima observed at ⟨110⟩ field directions in high fields disappear leaving minima only at ⟨112⟩ field directions. At still lower fields very sharp peaks develop corresponding to sudden switches in the magnetization direction as the field is rotated. These peaks are present up to fields of 4 or 5 kOe but are more accentuated at lower fields. For thick whiskers (several hundred microns in diameter) the switching peaks do not have much relation to the crystal symmetry and a large number of peaks may be observed as in Fig. 2(c). For thinner whiskers, the switching peaks become very sharp and narrow and follow the crystal symmetry more closely. However, it is clear that to some extent they are influenced by surface and shape anisotropies in the whisker. The sharp narrow peaks often represent an increase of resistance on the order of 50 to 80% such as shown in Fig. 7 for an 80-μ ⟨111⟩ whisker. These

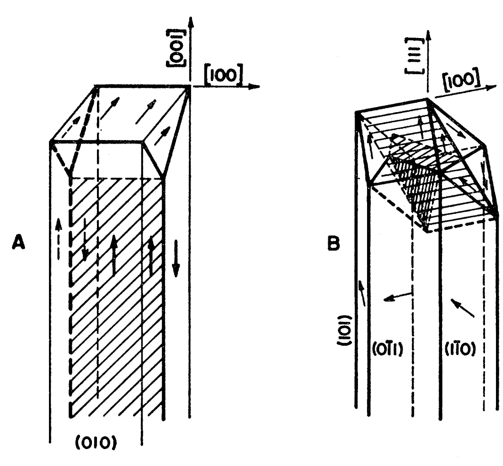

FIG. 5. Three-dimensional zero field domain structure in iron whiskers deduced from powder pattern evidence. (a) ⟨100⟩, (b) ⟨111⟩ (Coleman and Scott, Ref. 9).

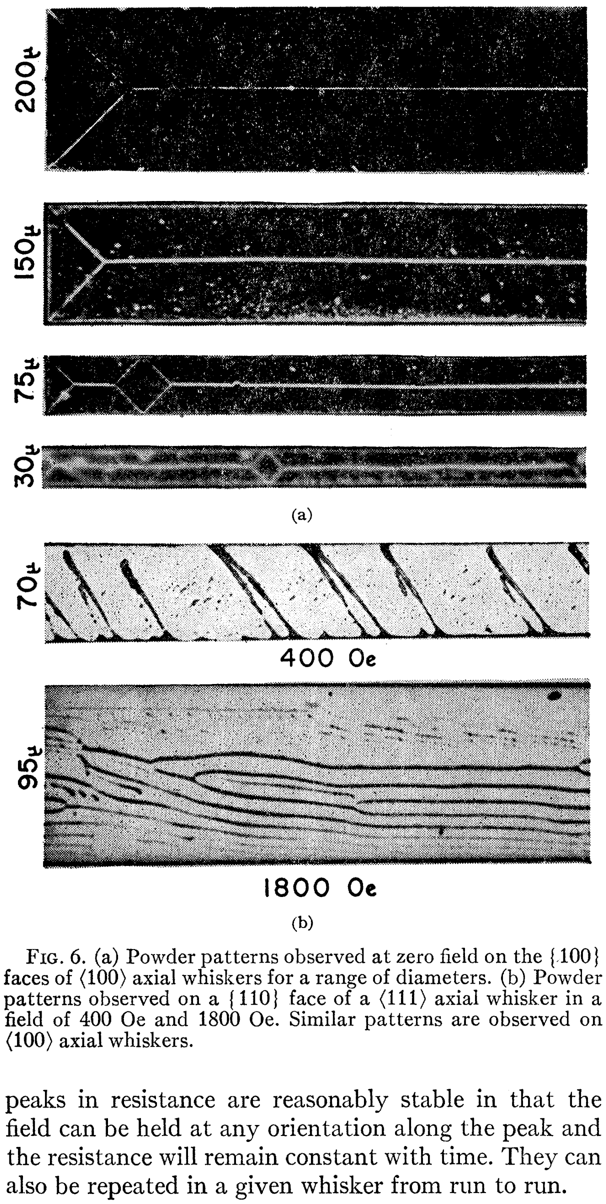

FIG. 6. (a) Powder patterns observed at zero field on the {100} faces of ⟨100⟩ axial whiskers for a range of diameters. (b) Powder patterns observed on a {110} face of a ⟨111⟩ axial whisker in a field of 400 Oe and 1800 Oe. Similar patterns are observed on ⟨100⟩ axial whiskers.

peaks in resistance are reasonably stable in that the field can be held at any orientation along the peak and the resistance will remain constant with time. They can also be repeated in a given whisker from run to run.

FIELD DEPENDENCE

Field dependence curves have been measured from 0 to 50 kOe for the three axial orientations ⟨111⟩, ⟨110⟩, and ⟨100⟩ and for a range of diameters from 40 to 400 μ. In the high-field region above magnetic saturation ($H>12$ kOe), the resistance rises faster than linearly with applied field **H**. If the resistance variation is described by $\rho(\mathbf{B})/\rho(0)=\text{const}B^m$, then m varies from 1 to 1.8 for the various orientations of crystal axis and **H** which have been measured. In a whisker of given diameter, the smallest values of m occur for orientations of **H** along the sharp minima observed in the rotation diagrams. However, all values of m observed so far have been >1. The value of m at a given orientation of **H** also depends markedly on the whisker diameter, decreasing toward 1 as the diameter of the whisker decreases. This can be seen in Fig. 4 which shows typical field dependence curves for various diameters and orientations. The reduction in the value of m for a given orientation of **H** as the whisker becomes thinner may be a mean free path effect since for the thin whiskers the diameter is on the order of the mean free path. Surface scattering could then limit the electron orbit and modify its contribution to the magnetoresistance.

Below about 12 kOe the slope of the resistance versus field curve exhibits a break and the resistance drops sharply with the magnetoresistance becoming negative at low fields for most of the cases measured. The depth and extent of the negative magnetoresistance region depends on the diameter of the whisker and also on the orientation of the magnetic field. In some cases the negative region has been observed to extend up to 6 kOe as in Figs. 4(a) and (b), but generally extends only to several thousand oersteds. The depth of the negative magnetoresistance region also varies over a wide range. The maximum decrease in resistance observed so far has been about 70% of the zero-field resistance. In general the negative region of magnetoresistance becomes smaller as the whisker diameter is reduced and for the 40-μ whisker measured in Fig. 4(c) has disappeared altogether, the magnetoresistance being positive for all field values and orientations of **H** which were measured.

A consistent increase in the residual resistance ratio $\rho_{RT}/\rho_{4.2°}$ is also observed as the size of the whisker is reduced. Representative values of $\rho_{RT}/\rho_{4.2°}$ for whiskers of various ranges of size are 268 for a 440 μ ⟨111⟩, 454 for a 100 μ ⟨111⟩, and 1963 for a 40 μ ⟨100⟩. The increase in $\rho_{RT}/\rho_{4.2°}$ is also accompanied by an increase in the helium temperature magnetoresistance ratio at high fields. Values of the magnetoresistance ratio $\rho(H)/\rho(0)$ at 50 kOe for the three whiskers referred to above are 26, 33, and 85. This would indicate a progressive increase in purity as the diameter decreases. Although the thin whiskers are selected from the same growth chambers as the thick whiskers, this difference in purity could result from the growth mechanism responsible for the thickening of the whisker. It is thought that impurities may play a major role in the thickening process.[6]

The negative region of magnetoresistance occurs for field values at which considerable domain structure exists in the whisker and can probably be attributed to the effects of domain wall scattering and spin-wave scattering as suggested by several authors.[5,7] Fowler, Fryer, and Treves[8] have in fact observed domains

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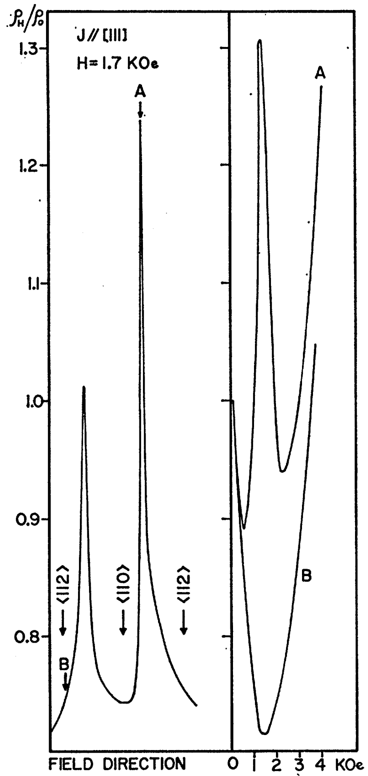

FIG. 7. (a) Rotation diagram obtained for a 80-μ ⟨111⟩ whisker in a field of 1700 Oe. (b) Field dependence curves measured for the field orientations labeled A and B in Fig. 7(a).

persisting in iron whiskers in fields up to 6000 Oe. The negative region appears to be very sensitive to the detailed development of domain structure and magnetization during application of a transverse field. The simple explanation that domain wall scattering is reduced upon application of the field because of a reduction in the number of walls by domain extension during magnetization does not seem to be a complete explanation, however. First of all, the zero-field domain structure in well-oriented whiskers seems to be the simplest type of domain structure which can exist in the whisker. This structure has been deduced using powder pattern techniques by Coleman and Scott[9] and by Graham and De Blois,[10] and is shown schematically in Fig. 5 for a ⟨100⟩ and ⟨111⟩ axial whisker. These structures were, of course, determined at room temperature, but there is no apparent reason why cooling to helium temperature should alter them. The simple domain patterns observed on ⟨100⟩ axial whiskers are shown in Fig. 6(a) and do not appear to vary appreciably as the diameter of the whisker is reduced over the range in which measurements have been made on the magnetoresistance. Application of a transverse field produces a much more complicated domain pattern in the whisker, examples of which are shown in Fig. 6(b) for fields up to 1800 Oe.

The low-field magnetoresistance as a function of magnetic field is also observed to vary from positive to negative depending on the orientation of the magnetic field relative to the crystal. An example of this effect is shown in Fig. 7 for an 80-μ ⟨111⟩ axial whisker. Figure 7(a) shows the rotation diagram obtained at 1700 Oe while Fig. 7(b) shows the field dependence curves measured for the orientations marked A and B on Fig. 7(a). For orientations of field corresponding to the peaks in the rotation diagram a sharp positive peak is observed in the field dependence of resistance. The only explanation for this seems to be that the detailed domain structure developing during magnetization is considerably different for the two orientations, although both structures should be more complicated than the zero-field domain structure. The field dependence curves are again reproducible and the resistance at any point of the field dependence curve is reasonably stable with time if the field is held at a constant value. A similar behavior has also been observed in ⟨100⟩ axial whiskers.

CONCLUSIONS

The transverse magnetoresistance measurements on iron whiskers have shown that they provide excellent specimens for both high- and low-field studies. In the high-field region the data are consistent with the behavior of a compensated metal and also indicates that open orbits are present on the Fermi surface. The field dependence has been studied from 0 to 50 kOe and has been shown to depend on the diameter of the whisker. In the high-field region the resistance is described by $\rho(B)/\rho(0)=\text{const}B^m$ where $1<m<2$. The value of m decreases toward 1 as the diameter of the whisker is decreased. The residual resistance ratio $\rho_{RT}/\rho_{4.2°}$ and the magnetoresistance ratio $\rho(H)/\rho(0)$ are also both observed to increase substantially as the diameter of the whisker is decreased.

In low fields an extensive region of negative magnetoresistance is often observed. The extent of this region has been shown to depend on the diameter of the whisker and is correlated with the magnetization process occurring below saturation. The resistance at low fields appears to depend on the detailed domain structure developing at low fields since both positive or negative magnetoresistance can be observed at the same field for different orientations of **H**. Further experiments will be required to analyze this effect in detail.

ACKNOWLEDGMENT

The authors wish to thank Phillip Sommer for constructing the sample holders and related equipment used in the experiment.

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[10] R. W. De Blois and C. D. Graham, J. Appl. Phys. **29**, 931 (1958).

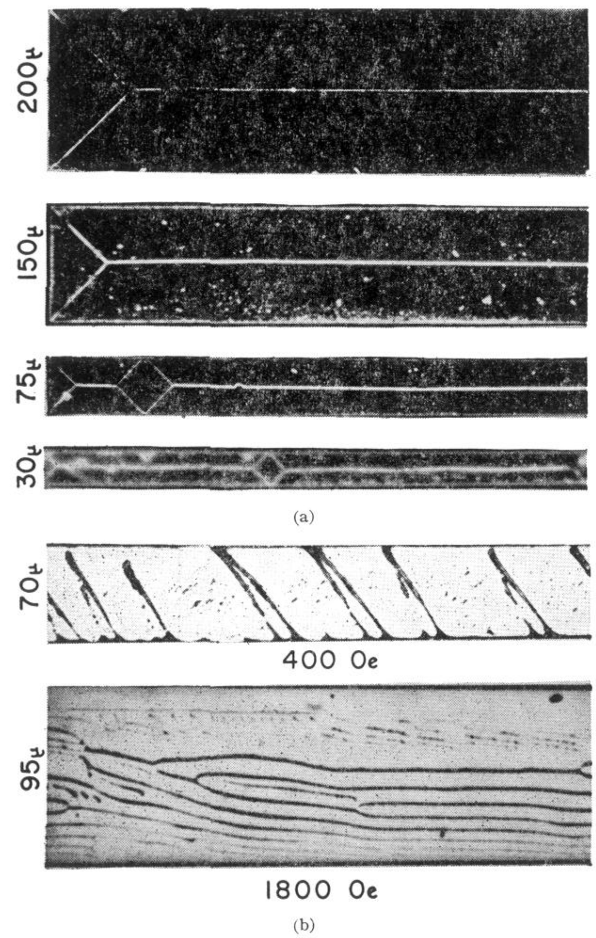

FIG. 6. (a) Powder patterns observed at zero field on the {100} faces of ⟨100⟩ axial whiskers for a range of diameters. (b) Powder patterns observed on a {110} face of a ⟨111⟩ axial whisker in a field of 400 Oe and 1800 Oe. Similar patterns are observed on ⟨100⟩ axial whiskers.